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DETECTING BUOY LIGHTS: EFFECTS OF MOTION AND LANTERN DIVERGENCE

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16. Abstract

The motion of a buoy may affect the probability that a navigational light signal is detected. ~~We studied~~ buoy motion is studied to quantify the effect it has on the detection range of a buoy's light signal.

Buoy motion data were taken from video recordings of standard USCG buoys in a variety of sea conditions. It became evident during the study that buoy motion is a combination of both list and roll.

Properties of a buoy signal light were mathematically combined with the buoy motion data to calculate detection ranges under various conditions. The detection ranges used in the analyses correspond to the distance at which a mariner has an 80% probability of detecting the buoy signal.

Results show that buoy motion is a problem. The present buoy lanterns provide an 80% probability of detection range which is only about half of the commonly accepted and published nominal range. This is true for most combinations of weather, buoy size, and flash characteristic. The effect of list alone contributed substantially to buoy signal degradation.

Further calculations showed that increasing the vertical divergence of a lens from the currently used 4.2° deg to between 8.3° deg and 10.0° (full-width, half maximum) will increase the detection range by approximately 40%. Keywords;

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METRIC CONVERSION FACTORS

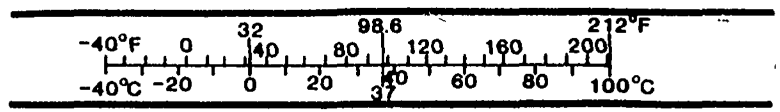
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price $2.25. SD Catalog No. C13.10.286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1.0 INTRODUCTION

The Coast Guard maintains approximately 4,100 lighted buoys in the waterways of the United States. The lanterns on these buoys consist of an omni-directional fresnel drum lens with a vertical filament lamp. The fresnel lens refracts the light of the lamp toward the optical (horizontal) plane to increase the apparent lamp intensity. This increase of intensity in the optical plane serves to increase the range at which the light may be detected.

Ideally, the axis of the buoy is vertical and the optical plane is horizontal. This results in the optical plane being coincident with the plane containing the mariner. Thus, most of the light signal is directed toward the mariner's eyes.

Unfortunately, buoys seldom remain perfectly vertical while on station. Many forces, such as wind, waves, and current, are constantly acting on a buoy, producing motion. This motion causes the optical plane to deviate from the horizontal. The motion of the buoy causes the high intensity light in the optical plane to be misdirected, as shown in Figure 1. Now, only a fraction of the peak light intensity is directed toward the mariner. The greater the angle between the horizontal plane and the optical plane, the less light provided to the mariner, and thus the shorter the detection range.

We desired to learn the extent to which buoy motion degrades a navigational signal. To make accurate calculations and predictions, we studied the motion of buoys on station in the First Coast Guard District. With this information we determined what corrections, if any, need be made to compensate for the degradation.

We hypothesized that five primary factors affect the detection range of buoy lights; buoy motion, flash duration, lens divergence, lantern intensity profile, and the observer's distance from the light. Buoy motion is, of course, the subject of this analysis. The motion, as stated earlier, misdirects the navigational signal from the horizontal plane of the mariner. Consider the flash duration. The longer a light is on, the easier one would expect it to be to detect the light. Lens divergence is the amount of vertical spread designed into the lantern. The intensity profile is directly related to the divergence of the lens; it is that fraction of the peak intensity which is emitted from the lantern at any given vertical angle. Both these factors describe the amount of light projected by a lantern and thereby affect the ability to detect the light. Finally, the observer's distance was taken into account. Intuitively, one expects the probability of detection (POD) to increase as the distance from the light decreases.

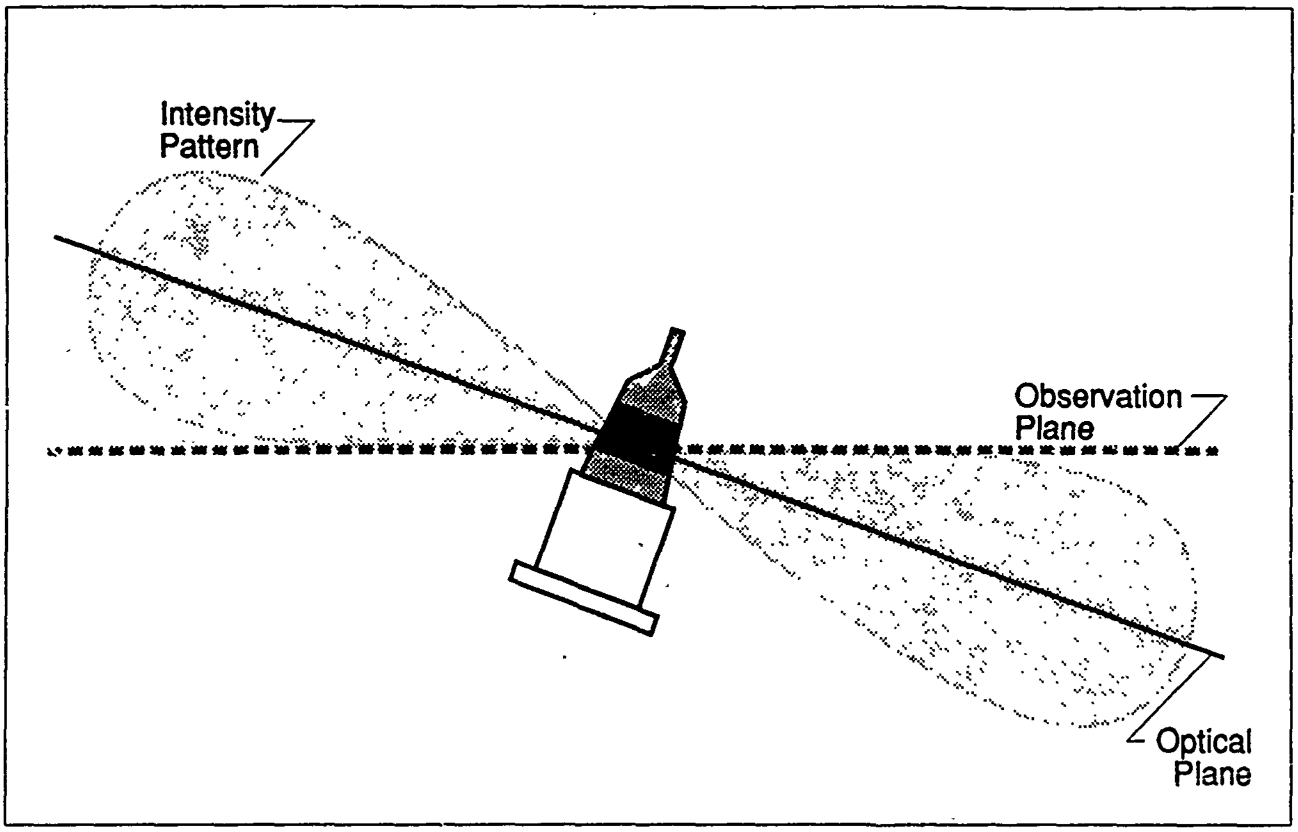

FIGURE 1. Effect of Buoy Angle on Observed Intensity

Previous efforts in this area were conducted by Feingold, et. al., [Ref. 1] and Hirsch [Ref. 2], but some of the factors considered here were ignored by these studies. Feingold did not consider observer distance from the buoy or the lantern intensity profile. Hirsch ignored the effects of buoy flash duration.

In this study, we quantify the detection range of signal lights on buoys with various degrees of roll and list. This work is a continuation of the effort started by Brown, [Ref. 3].

2.0 APPROACH

We remotely recorded on video tape the motion of operational buoys from conveniently located shore points in the First Coast Guard District. Buoys were chosen to represent all relevant buoy sizes in various sea conditions. We recorded buoy motion through a 600mm telephoto lens to increase the range of our video recording system. We then extracted time-series motion data from the video recordings in the laboratory.

The time-series motion data consist of periodic measurements of the angle between the buoy's vertical axis and a normal to the horizon. The data were combined with lantern intensity measurements to calculate time-series intensity data. This information was, in turn, modified to account for flash characteristic and distance between observer and the buoy. We used the resulting time-series of light intensity to calculate the probability that an observer would see the light over one flash period in 1000 randomly selected observations.

We defined the detection range of a buoy as that distance where sufficient light intensity was provided such that an observer would detect 80% of the flashes. Detecting the light means that the amount of light delivered to the observer during the observation exceeds the visual threshold, commonly accepted to be 0.67 sea-mile-candela.

This approach involves computer modeling of several aspects of the buoy motion problem. As with any modeling effort, we need to accept several assumptions to add credibility to the results of this study.

2.1 Assumptions

Assumptions a and c through f are the same as those of Brown [Ref. 3, pp. 6-7]. They are repeated here for easy reference. Assumption b has been altered to reflect the probability of detecting a single flash event and thereby simplifying our analysis. Assumptions g, h, and i have been added for this analysis.

a. Buoy motion was recorded in only one plane. The mariner is located in this plane. Effects of buoy motion in this plane of observation are representative of effects of buoy motion in all other planes of observation.

b. The mariner knows where and when to look for the buoy signal and only a single flash is considered. Thus, if the flash produces at least 0.67 sea-mile-candela at the observer's position, it is detected.

c. The lamp flashes with instantaneous rise and fall times. Lamp filament nigrescence time effects are considered minimal compared to buoy motion effects. The ideal square flash pulse is modified only by buoy motion and the vertical divergence of the lantern.

d. The Schmidt-Clausen method [Ref. 4] determines the effective intensity (EFI) for each flash pulse. Flash pulse duration defines the limits of integration for this method, not the actual instantaneous intensity in the horizontal plane.

e. If a mariner detects a flash pulse at a given distance, he will also detect the same pulse at shorter distances.

f. Visibility is assumed to be constant at 10 nautical miles (0.74 atmospheric transmissivity).

g. Background lighting is assumed to be negligible.

h. The twelve data sets of buoy motion recorded for this study are representative of the buoy population as a whole.

i. A Gaussian curve can be used to approximate the vertical intensity profile of a lens.

3.0 DATA ACQUISITION

3.1 Buoy Motion Collection Equipment

Buoy motion data were collected with a video recording system. A Panasonic WV-3260/8AF video camera with a Canon FD600mm telephoto lens was adequate for viewing a buoy at a range of up to 1.5 miles. We recorded the motion with a Panasonic AG-2400 video cassette recorder (VCR).

We selected Panasonic equipment because of the special features the equipment provides. The following list describes these features and their purpose in data acquisition.

- Time and date display incorporated into the recording - provides a means of establishing a data sampling rate and also retains information necessary to compute tidal conditions at a later time.

- Positive / negative imagery - aids in transferring motion information from the television to the computer by increasing the contrast between the buoy and the water background.

- Removable lens with adaptors - makes it possible to put a lens from a different manufacturer on the video camera. In this case, a Canon FD600mm telephoto lens was used.

- Strobe effect shutter - produces clear still frame images which aid in transferring the motion information to a computer file.

3.2 Analog to Digital Conversion of the Motion Data

To establish the angle of a buoy, we constructed the angle measuring device shown in the lower half of Figure 2. The device consists of a Plexiglas sheet attached to a digital shaft encoder. The Plexiglas sheet has horizontal and vertical lines inscribed at 0.5" intervals. The cross-hashed Plexiglas screen rotates on the axle of the digital shaft encoder in front of a television screen and is aligned by eye with the edge of the buoy.

With a buoy video image paused on the television, the horizontal lines on the screen were aligned with the horizon on the television image to zero the shaft encoder. This step makes the vertical lines on the screen normal to the horizon. By paralleling the vertical lines to

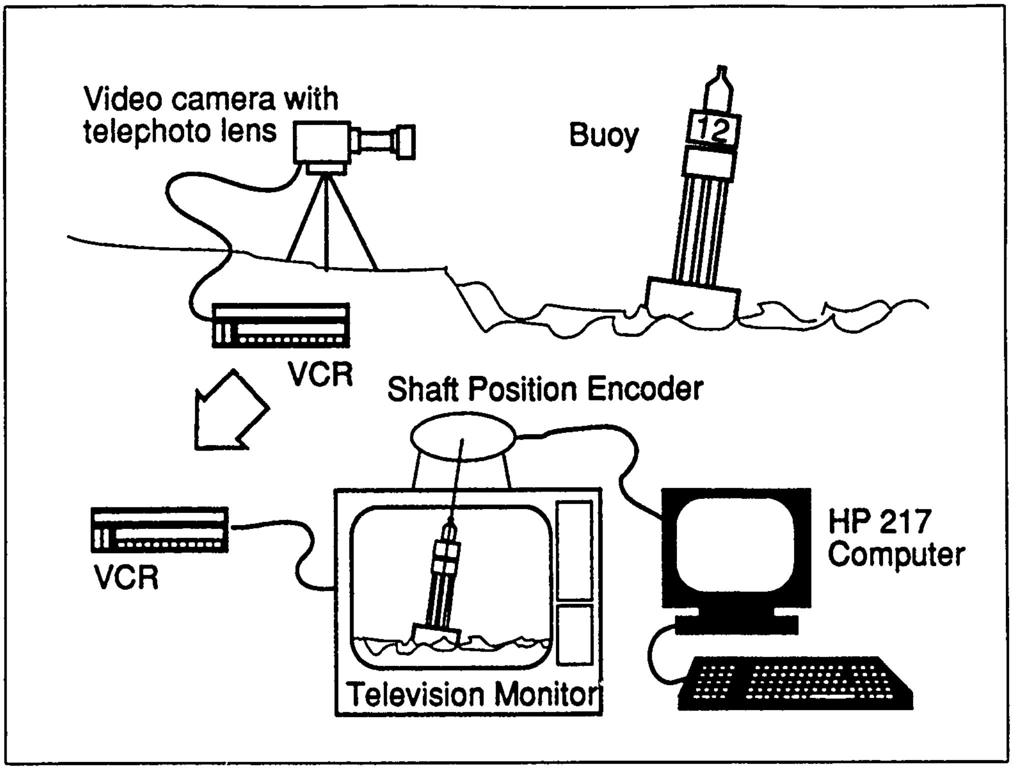

FIGURE 2. Buoy Motion Video Recording System

the buoy image, the digital shaft encoder represents the angle between the buoy and the normal to the horizon. The angular settings of the shaft encoder were automatically recorded by an HP217 computer. The buoy angle measurements can be repeated with an accuracy of $\pm 0.2°$.

The pause and frame-by-frame advance features of the VCR and the time/date information recorded on the video tapes allowed the buoy images to be sampled at a rate of up to 30 Hz. As measurements were taken by hand in this analysis, 1 Hz[1] was used to make the task tolerable. Twelve 10-minute data files of buoy angle versus time were obtained from nearly 10 hours of video recordings.

Measurements were obtained for 9x32, 8x26, 7x17, 6x20, and 5x11 buoys. We attempted to select buoys for this study that were exposed to the open ocean, yet within 1.5 miles from land due to the range limitations of our video system. Of all the buoys recorded, only the 7x17 was not exposed to the open ocean. Table 1 lists the buoys and their locations. The file designations in Table 1 will serve to identify the location of each buoy through the rest of this report.

TABLE 1
BUOY LOCATIONS

BUOY	LOCATION
9 x 32	South of Gloucester, MA. Marks disposal area.
8 x 26-A	South of New London, CT. New London Harbor entrance buoy.
8 x 26-B	Off Watch Hill, RI.
7 x 17	Providence River, Warwick, RI. Channel Buoy 23.
6 x 20	South of New London, CT. Pine Island light 2.
5 x 11	East of Green Harbor, MA. Green Harbor entrance buoy.

1 Work performed previously by LT D. Brown, USCG, [Reference 3, p. 39] showed the prevalent roll period of an 8x26 buoy to be 5.7 seconds or 0.175 Hz. Likewise, for a 5x11 buoy the period was found to be 4.6 seconds or 0.217 Hz. Using the Nyquist sampling criteria [Reference 5, pp. 121-122], the motion of the buoy can be described by sampling at a rate of at least twice the frequency of the motion. In this case, the sampling rate of 1 Hertz is well above the minimum sampling rates of 0.35 Hz required for an 8x26 buoy or 0.434 Hz required for a 5x11 buoy. Hence, the sampling rate of 1 Hz is adequate in describing the motion of a buoy over a period of time.

Sea conditions were classified as being either 0'-3' or 3'-6'; seas of 6'+ were not considered to be typical conditions. Table 2 lists the buoy data files and the sea conditions experienced during the recordings. Tidal currents during the video recordings were calculated and are also supplied in Table 2.

4.0 DATA ANALYSIS

Before any probabilities can be calculated, it is necessary to define a lantern intensity profile. The intensity profile is used to equate a buoy's angle to the horizontal intensity of the buoy signal light. For our intensity profile, we used the measured output of a standard Coast Guard optic, a yellow 155mm lantern with a 1.15 amp lamp. This intensity profile was a standard established by Brown in his report [Ref. 3], and is used in this analysis to establish continuity between the two studies.

TABLE 2
VIDEO BUOY ROLL FILES

BUOY	SAMPLE NO.	SEAS (ft.)	TIDAL CURRENT (kts)
9 x 32	(1)	0-3	0.4
	(2)	3-6	slack
8 x 26-A	(1)	0-3	0.24
	(2)	0-3	0.2
	(3)	0-3	slack
8 x 26-B	(1)	3-6	1.34
	(2)	3-6	0.9
7 x 17	(1)	0-3	*
6 x 20	(1)	0-3	0.17
	(2)	3-6	0.13
5 x 11	(1)	0-3	0.8
	(2)	0-3	0.63

* The 7x17 buoy was recorded in the Providence River, and thus tidal current information does not apply at this location.

The measured intensity profile of the standard optic is shown in Figure 3. The divergence of the lantern is determined by finding the angular spread of light at half the peak intensity. In this particular case, the peak intensity is 232 candela. The horizontal line then, at 116 candela, shows that the divergence of this optic extends from -2.2° to +2.0°. Therefore, the standard Coast Guard optic has a divergence of 4.2°.

Flash characteristics must also be included before probabilities can be calculated. We used three standard flash characteristics in this analysis. These flash characteristics are the three most commonly found on aids to navigation. The characteristics and the buoy populations they represent are listed in Table 3.

TABLE 3
BUOY POPULATION BY FLASH CHARACTERISTIC*

CHARACTERISTIC		PERCENTAGE OF THE BUOY POPULATION
Flashing 6 (0.6)**	-	6
Flashing 4 (0.4)**	-	69
Flashing 2.5 (0.3)**	-	8

* Reprinted from Reference 3, p. 31. Buoy populations represent a random sampling of 62 buoys from the Coast Guard light list.

** The values in parenthesis represent the flash duration in seconds.

4.1 Computer Procedures

The computer changes the buoy angle versus time files to a record of horizontal intensity versus time by simple substitution. Each buoy angle in the time record has a corresponding angle in the lantern intensity profile. The intensity for each sequential buoy angle is copied into a new file. The resultant record is a time sequence of intensity in the horizontal plane.

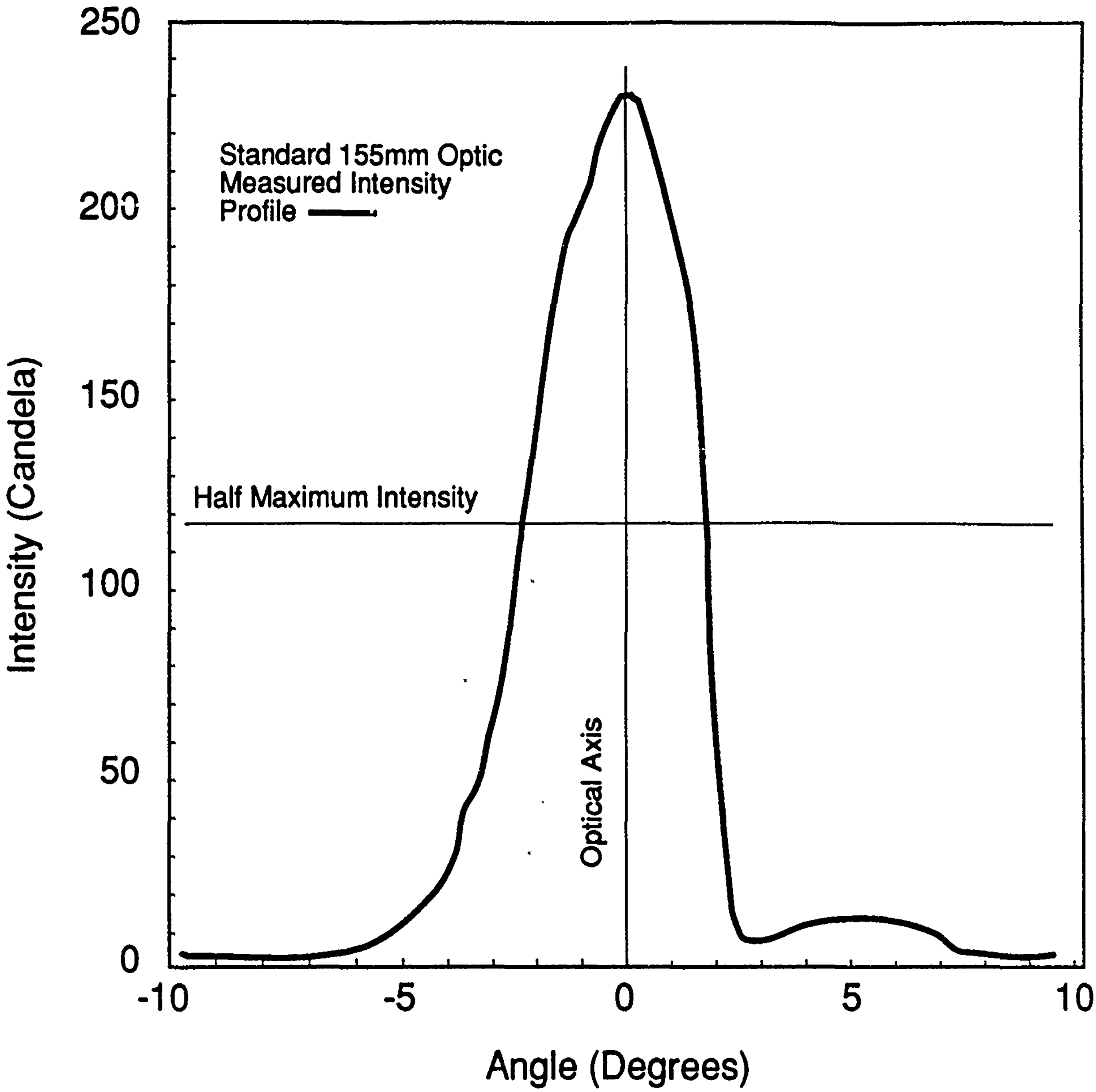

FIGURE 3. Vertical Intensity Profile of a Standard Coast Guard Optic

A simulated flash is placed randomly in the intensity versus time file. The observation distance is varied from 0.1 nm to 8.0 nm in 0.1 nm increments. If the effective intensity at a given observation distance is in excess of 0.67 sea-mile-candela, the signal is considered to be detected. The random placement of flashes is repeated 1000 times to calculate the probability of detection as a function of the observation distance.

Of interest in the design of navigational aids is the distance at which 80% of all the light signals are seen. Therefore, the distance at which 80% of the flash pulses are seen is called the detection range or the 80% POD range. This range will be the standard by which all comparisons are made throughout this report.

5.0 RESULTS

5.1 Buoy Roll and List

There are only two components of buoy motion which will affect the detection probability of a buoy's light signal; buoy roll and list. Buoy roll is an oscillation in the buoy angle. Buoy list is a constant angle of offset about which the buoy oscillates. Figure 4 illustrates buoy list and roll. Table 4 shows the list and roll amplitudes for each buoy measured.

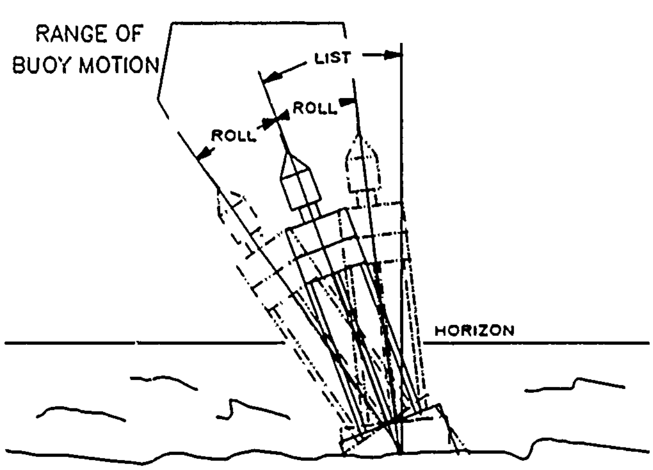

FIGURE 4 – REPRESENTATION OF BUOY ROLL AND LIST

RMS (root mean square) roll amplitude varied between 0.6° and 7.5°. Roll amplitude was found to be positively correlated with the sea conditions (correlation coefficient r = 0.68). That is, the sea state can be used as a predictor of the roll amplitude; the higher the sea state, the higher the roll amplitude. We see in Table 4 that the only time the roll amplitude exceeds the list is when the seas are greater than three feet, and then in only three of four cases.

List, on the other hand, was independent of sea conditions (correlation coefficient r = -0.09). That is, the list cannot be predicted from knowledge of the sea state. One would expect that a buoy designed to float vertically in the water would have a list near zero. Such is not the case. The list varied between 1.1° and 7.4°. Additionally, list did not remain constant for any particular buoy. A buoy observed at different times will have different lists. This is illustrated in Table 4.

TABLE 4
BUOY LIST AND RMS ROLL AMPLITUDE

BUOY	SAMPLE NO.	SEAS (ft.)	LIST (deg.)	RMS ROLL AMPLITUDE (deg.)*
9 x 32	(1)	0-3	5.1	1.7
	(2)	3-6	2.6	1.8
8 x 26-A	(1)	0-3	2.8	0.6
	(2)	0-3	7.4	1.0
	(3)	0-3	2.9	0.9
8 x 26-B	(1)	3-6	1.9	2.5
	(2)	3-6	1.1	4.0
7 x 17	(1)	0-3	1.3	0.9
6 x 20	(1)	0-3	3.0	1.4
	(2)	3-6	6.9	7.5
5 x 11	(1)	0-3	3.3	2.2
	(2)	0-3	2.3	1.8

* The maximum average roll is the sum of list and amplitude. The minimum average roll is list minus amplitude.

5.2 Divergence

We anticipated that altering the divergence of the standard Coast Guard optic would affect the probability of detection calculations, and perhaps minimize the effects of buoy motion. We could not construct a large number of lanterns with varying divergences for analysis, so we mathematically modeled lantern intensity profiles. Gaussian curves were generated which have the same total flux (area under the curve) as the previously measured Coast Guard 155mm lantern with a 1.15 amp lamp. The computer maintains the total flux by accounting for changes in the divergence with alterations in the peak intensity. Hence, any increases in the divergence will decrease the peak intensity, and vice versa.

Maintaining a constant total lamp flux gives the effect of standardizing the lamp used in the lanterns of various divergences. Therefore, direct comparisons between the 80% POD ranges for various lantern divergences can be made.

Figure 5 compares the actual, measured lantern profile of the Coast Guard standard lantern to a mathematically produced Gaussian curve with 4.2° full-width, half-maximum points. The Gaussian estimation is a good approximation of the actual lantern intensity profile (supports assumption i).

The simulated lantern files created for this analysis are listed in Table 5.

TABLE 5
GAUSSIAN LANTERN DATA FILES

FWHM* (deg.)	PEAK INTENSITY (cd.)	NOMINAL RANGE FOR A NON-FLASHING LIGHT (nm)
3.0	329.8	7.4
4.0	235.6	6.8
5.0	198.0	6.5
6.0	165.0	6.2
7.0	141.5	6.0
7.5	132.1	5.8
8.0	123.9	5.7
9.0	110.2	5.6
10.0	99.2	5.4
12.5	79.5	5.1
15.0	66.3	4.8
20.0	50.0	4.4

* FWHM Full-Width, Half-Maximum: describes the vertical divergence of the lens.

The nominal ranges for non-flashing lamps in lanterns of various divergences are provided in Table 5. The nominal range is the published performance criterion of a buoy, but this is

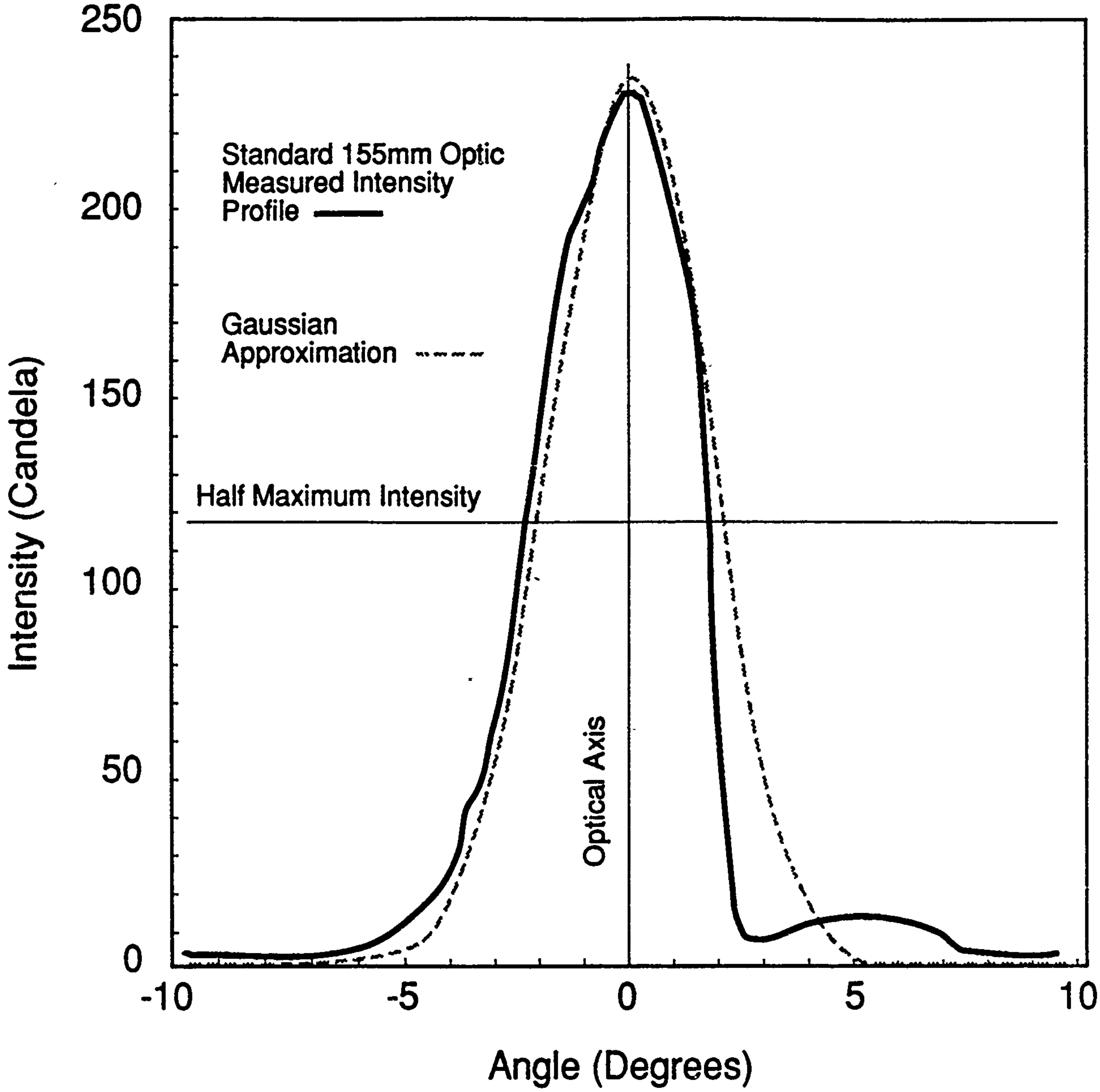

FIGURE 5. Vertical Intensity Profile Comparison

not the distance at which a buoy is detected 80% of the time. The published nominal range is the range at which the peak intensity of the light reaches 0.67 sea-mile-candela given an atmospheric visibility of 10 nm.

5.3 Probability of Detection and the Standard Coast Guard Optic

The divergence of the standard Coast Guard lantern is 4.2°. With this standard divergence and the flashing 4 characteristic, the nominal range of a buoy signal is 6 nm[2]. The 80% POD ranges calculated for a 4.2° lens in the 12 motion files vary from a high of 5.25 nm to a low of 0.0 nm. An 80% POD range of 5.25 nm is attained by the 7x17 buoy with 1.3° of list and 0.9° of RMS roll. The 0.0 nm range is found with a 6x20 buoy with a 6.9° list and a 7.5° RMS roll. Table 6 shows the 80% POD ranges achieved with a lens of 4.2° divergence. The percentage of the nominal range (6.0 nm) achieved with this divergence is also provided.

TABLE 6
EFFECT OF ROLL AND LIST ON THE PROBABILITY OF DETECTION
LANTERN DIVERGENCE 4.2

BUOY	SAMPLE NO.		80% POD RANGE nm	PERCENTAGE OF THE NOMINAL RANGE (6 nm)
9 x 32	(1)		0.79	13.2
	(2)		3.45	57.5
8 x 26-A	(1)		3.91	65.2
	(2)		0.30	5.0
	(3)		3.50	58.3
8 x 26-B	(1)		3.68	61.3
	(2)		2.82	47.0
7 x 17	(1)		5.25	87.5
6 x 20	(1)		3.15	52.5
	(2)		0.00	0.0
5 x 11	(1)		2.33	38.8
	(2)		3.98	66.3
		Average	2.76	46.1

2 The Schmidt-Clausen method [Ref. 4] was used to calculate the luminous intensity, and thereby the nominal range of a flashing light.

5.4 Flash Characteristics

Eighty percent (80%) POD ranges vary greatly between buoys and conditions, but not across flash characteristics. During the analysis it was found that the flash on-time was a critical variable that determined the 80% POD range. This dependence is the result of effective intensity calculations which are directly proportional to the flash pulse length. To illustrate this point, Figure 6 is provided. Figure 6 is a plot of the 80% POD range as a function of divergence. Only the 80% POD ranges for one buoy file, file 8x26-A(3), are plotted on the graph for the Flashing 6, the Flashing 4, and the Flashing 2.5 characteristics. Note that the curves are essentially parallel. Any effects of divergence evident in one of these curves are evident in the other two curves, regardless of flash characteristic. Each motion file produces a set of similar curves. Therefore, the Flashing 4 characteristic, being the most prevalent, is used exclusively throughout the remainder of this analysis.

6.0 DISCUSSION

6.1 Divergence and the Probability of Detection

Figures 7 through 10 show the effects of altering the divergence on the 80% POD ranges. A Flashing 4 characteristic was used in generating all the 80% POD ranges shown in these figures. The nominal range as a function of divergence for the Flashing 4 characteristic is provided on the figures as a reference. Note that there is typically a dramatic rise in the POD at the lower divergences (3° to 6°) and a gentle decline at the higher divergences (12° and higher) which tends to parallel the nominal range curve. It is evident that the 80% POD range can be maximized by adjusting the lantern divergence to compensate for roll and list. Table 7 shows the divergences that yield the maximum 80% POD range for each motion file. So as not to limit ourselves to a specific optimum divergence for each buoy motion file, we allowed a 0.1 nm variance in the 80% POD range. With this 0.1 nm variance, we obtained a divergence span for each curve.

The selection of a 0.1 nm variance is arbitrary. Decreasing the value of this variance will narrow the span of divergences that maximize the POD. Similarly, an increase in this variance will increase the span of divergences. Figure 11 graphically displays the information in Table 7. Figure 11 shows that the 80% POD range of 8 of the 12 buoy motion files will be maximized with a divergence between 8.3° and 10.0°. Figures 12 and 13 show the effects of altering the acceptable variance to 0.05 nm and 0.2 nm respectively. The divergence for maximization from Figure 12 is very nearly 9.0°. Figure 13 gives us an acceptable divergence span from 7.5° to 11.6°.

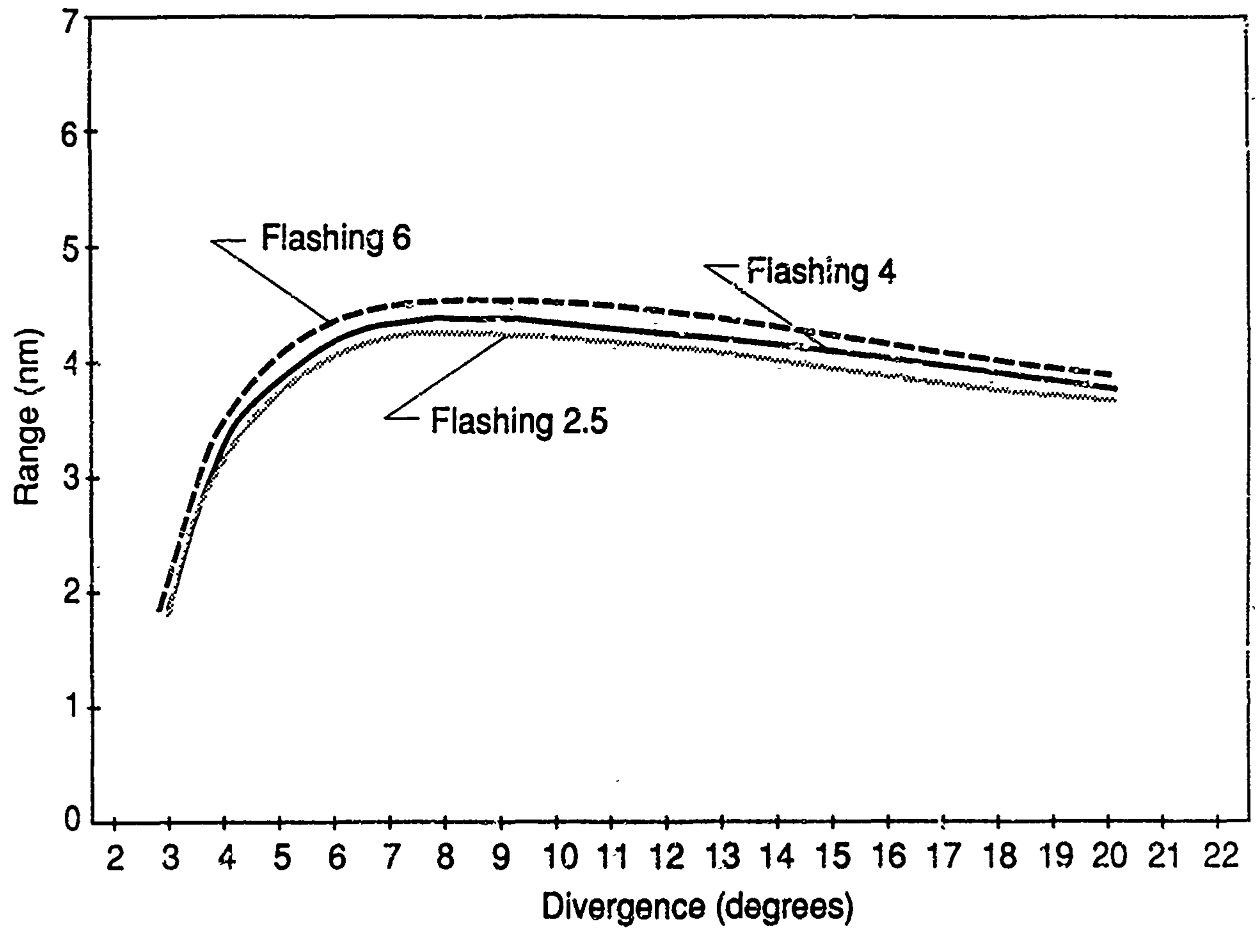

FIGURE 6. 80% POD Range as a Function of Flash Characteristic for Buoy Motion File 8x26 A(3)

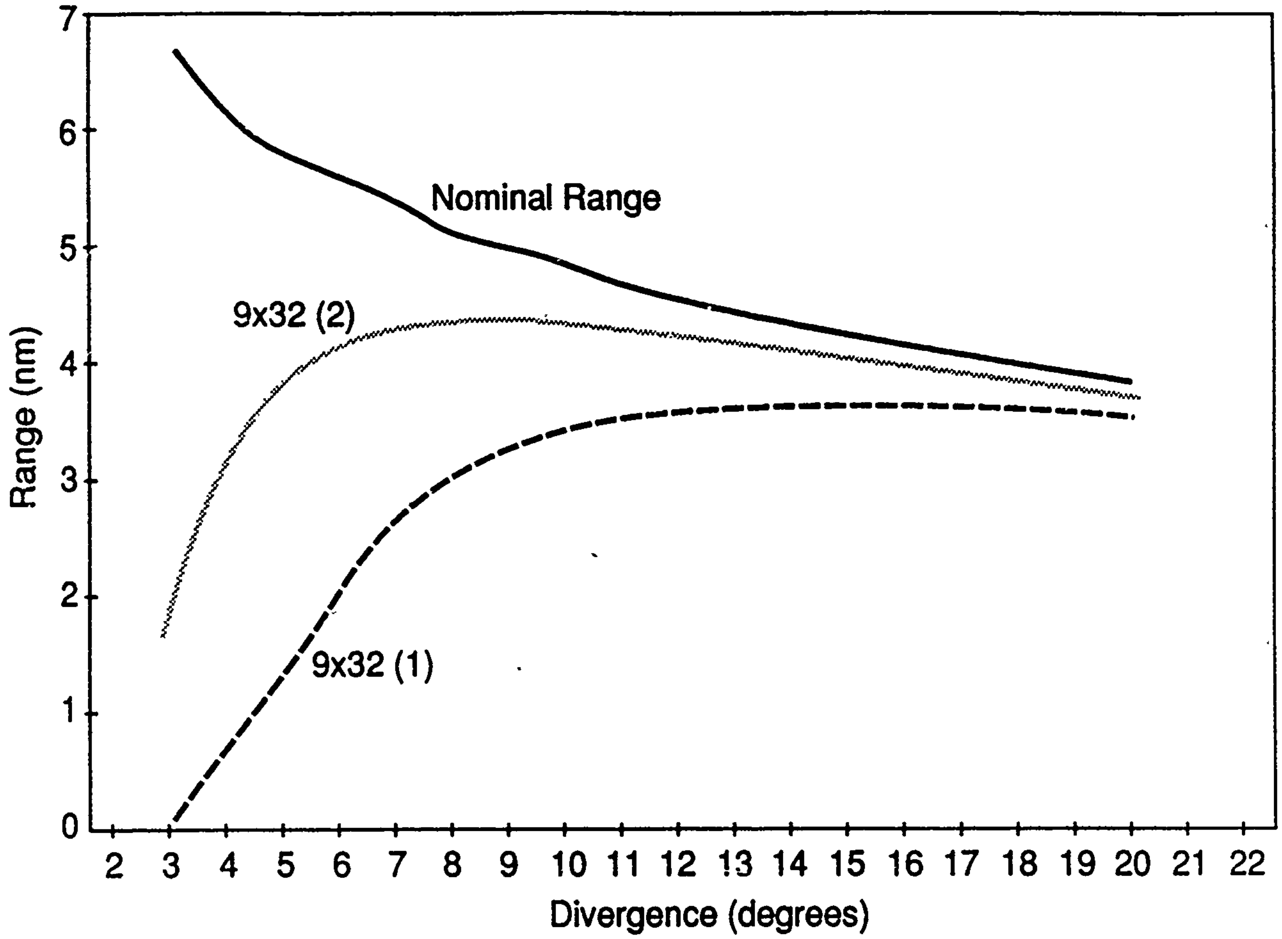

FIGURE 7. 80% POD Range vs Divergence for a 9x32 Buoy

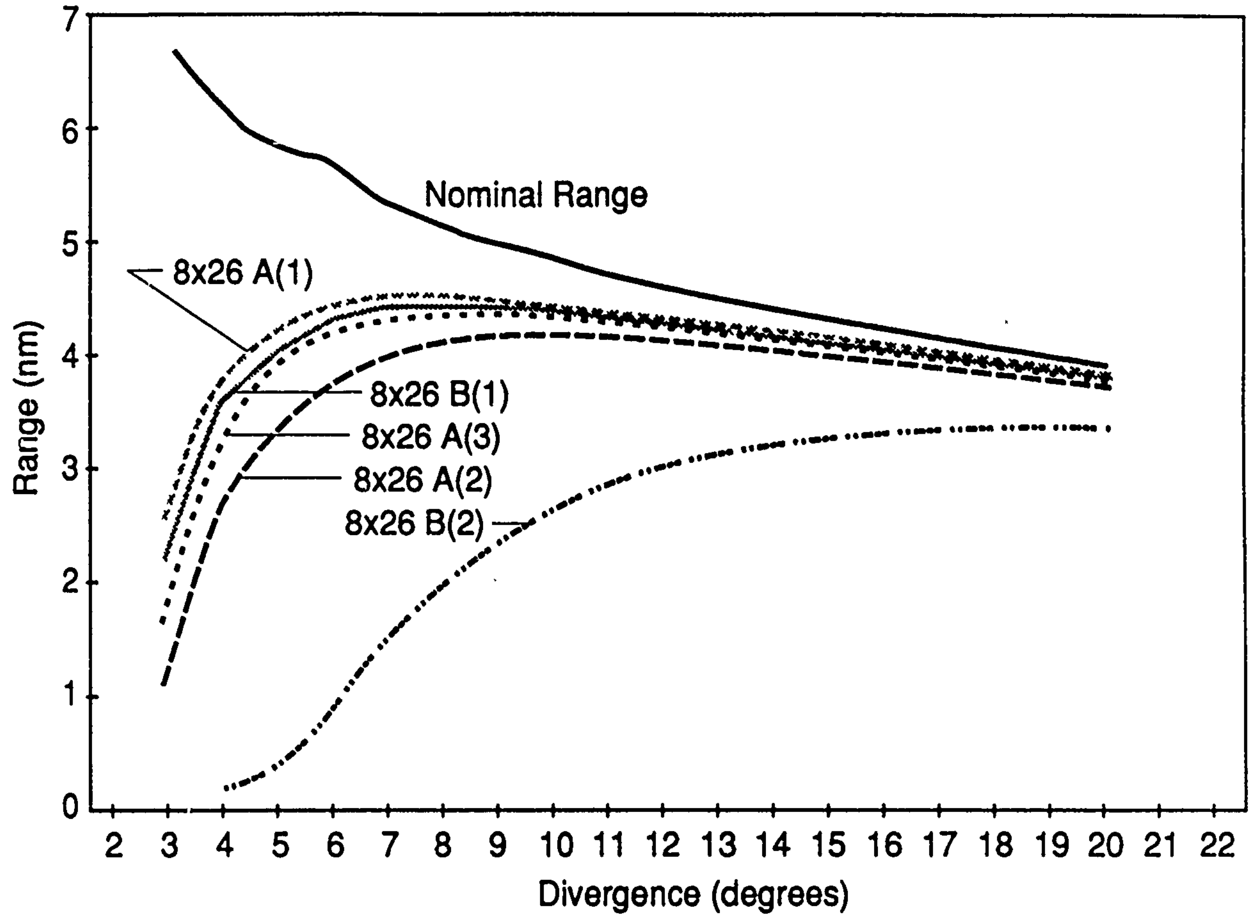

FIGURE 8. 80% POD Range vs Divergence for 8x26 Buoys

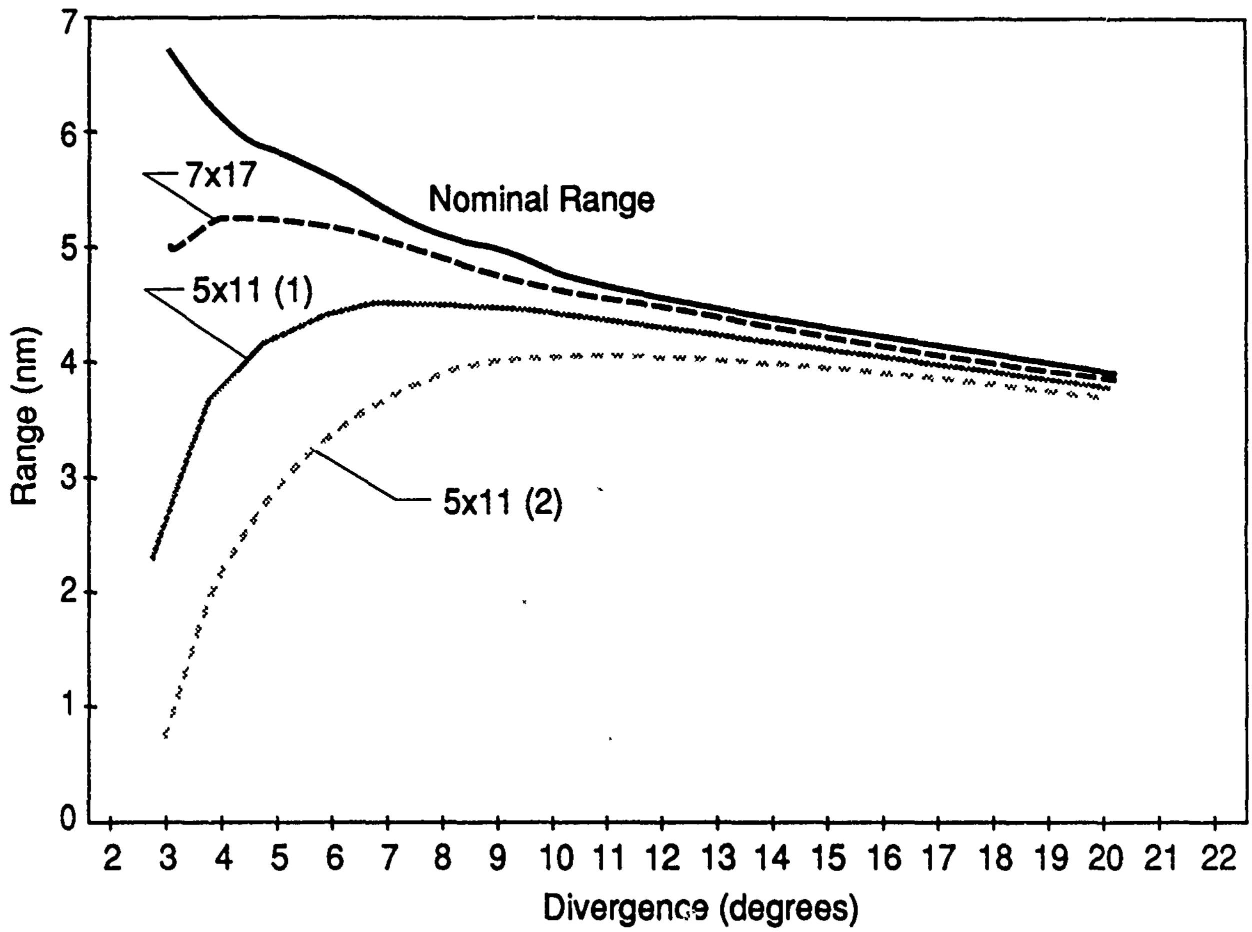

FIGURE 9. 80% POD Range vs Divergence for 7x17 and 5x11 Buoys

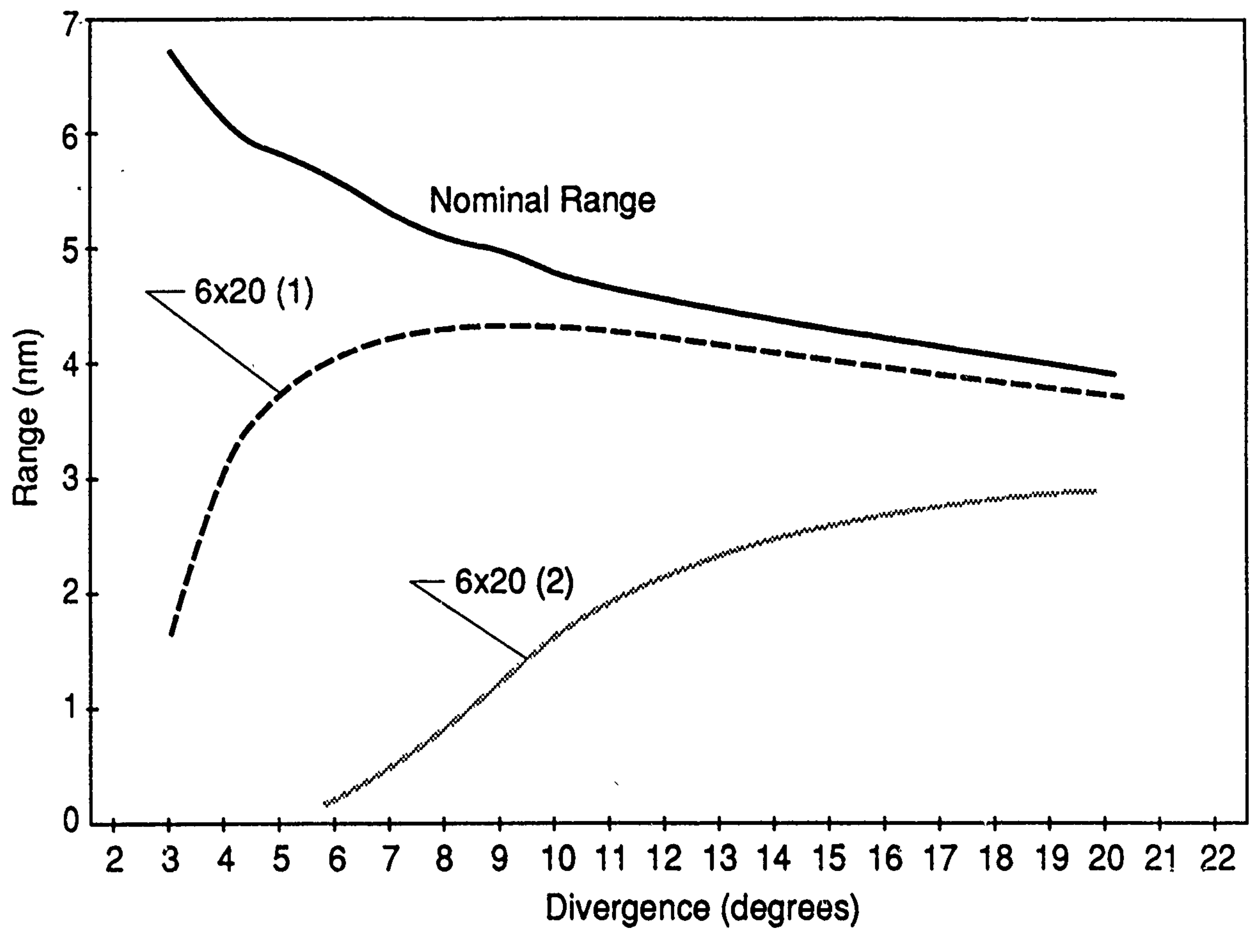

FIGURE 10. 80% POD Range vs Divergence for a 6x20 Buoy

TABLE 7

DIVERGENCES WHICH MAXIMIZE THE 80% POD RANGE

BUOY	SAMPLE NO.	DIVERGENCE SPAN (deg.)	MAXIMUM 80% POD RANGE (nm)	DIVERGENCE (deg.)
9 x 32	(1)	11.6 - 20.0	3.68	15.0
	(2)	6.6 - 11.5	4.36	9.0
8 x 26-A	(1)	6.0 - 10.0	4.52	7.5
	(2)	20.0+	3.38*	20.0+
	(3)	6.6 - 11.3	4.38	8.0
8 x 26-B	(1)	6.4 - 10.8	4.44	8.0
	(2)	7.5 - 13.2	4.19	10.0
7 x 17	(1)	3.6 - 6.0	5.25	4.0
6 x 20	(1)	7.0 - 12.0	4.28	9.0
	(2)	20.0+	2.98*	20.0+
5 x 11	(1)	8.3 - 14.7	4.06	10.0
	(2)	5.8 - 10.2	4.53	7.5

* Ranges attained with a divergence of 20°. Larger divergences may yield a greater range.

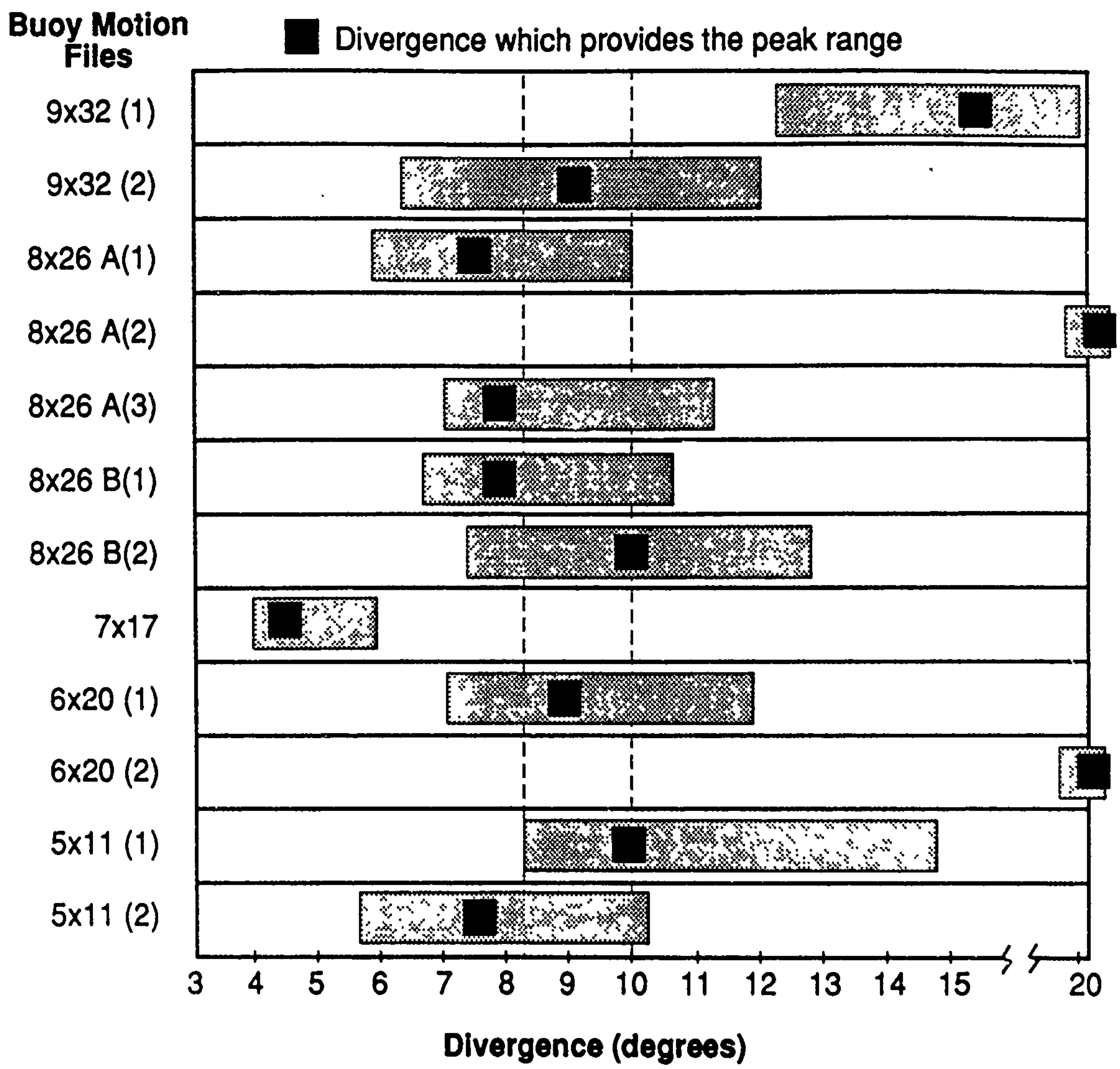

FIGURE 11. Divergences Which Maximize the 80% POD Range for Each Motion File (0.1 nm variance from the peak)

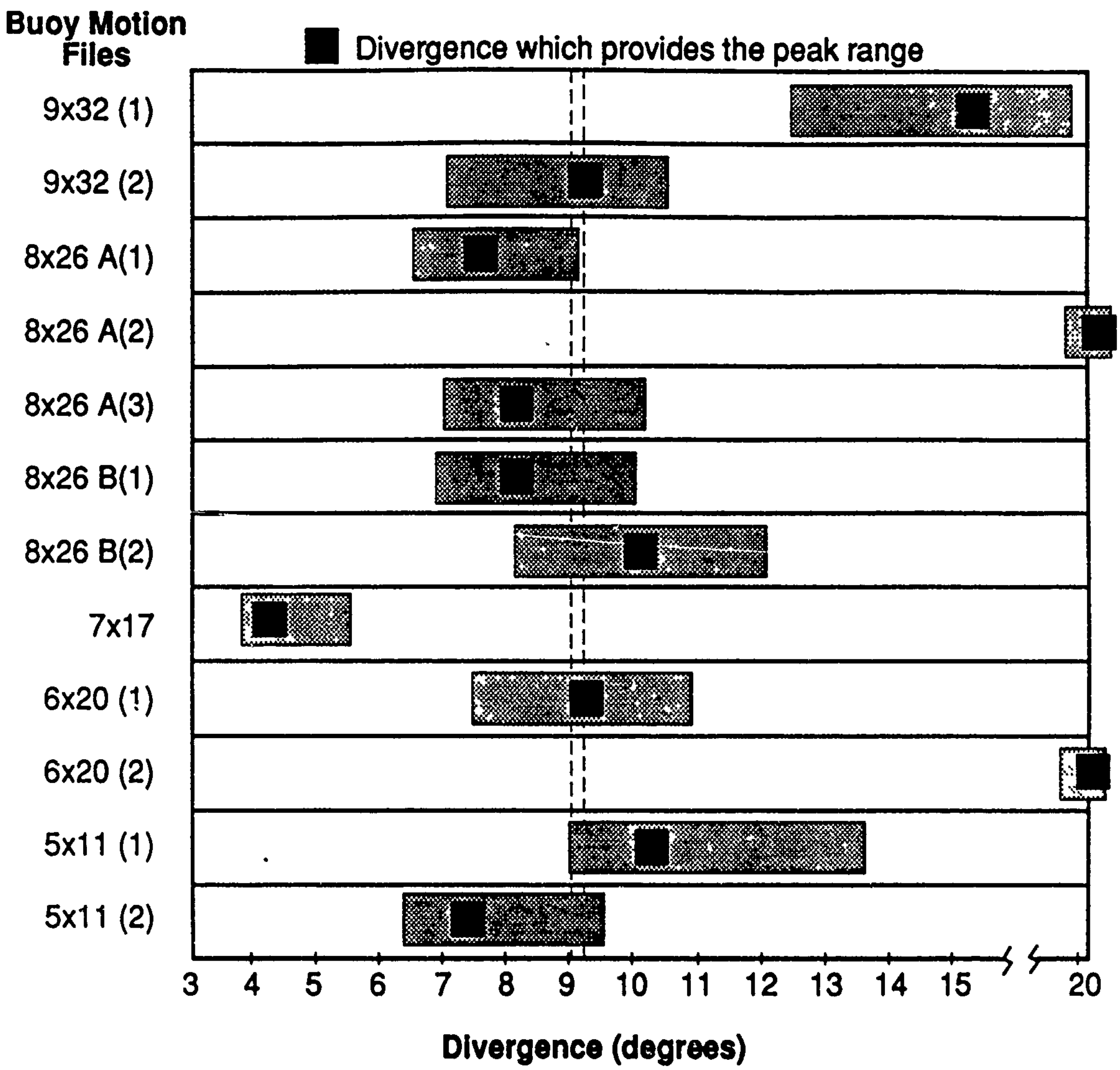

FIGURE 12. Divergences Which Maximize the 80% POD Range for Each Motion File (0.05 nm variance from the peak)

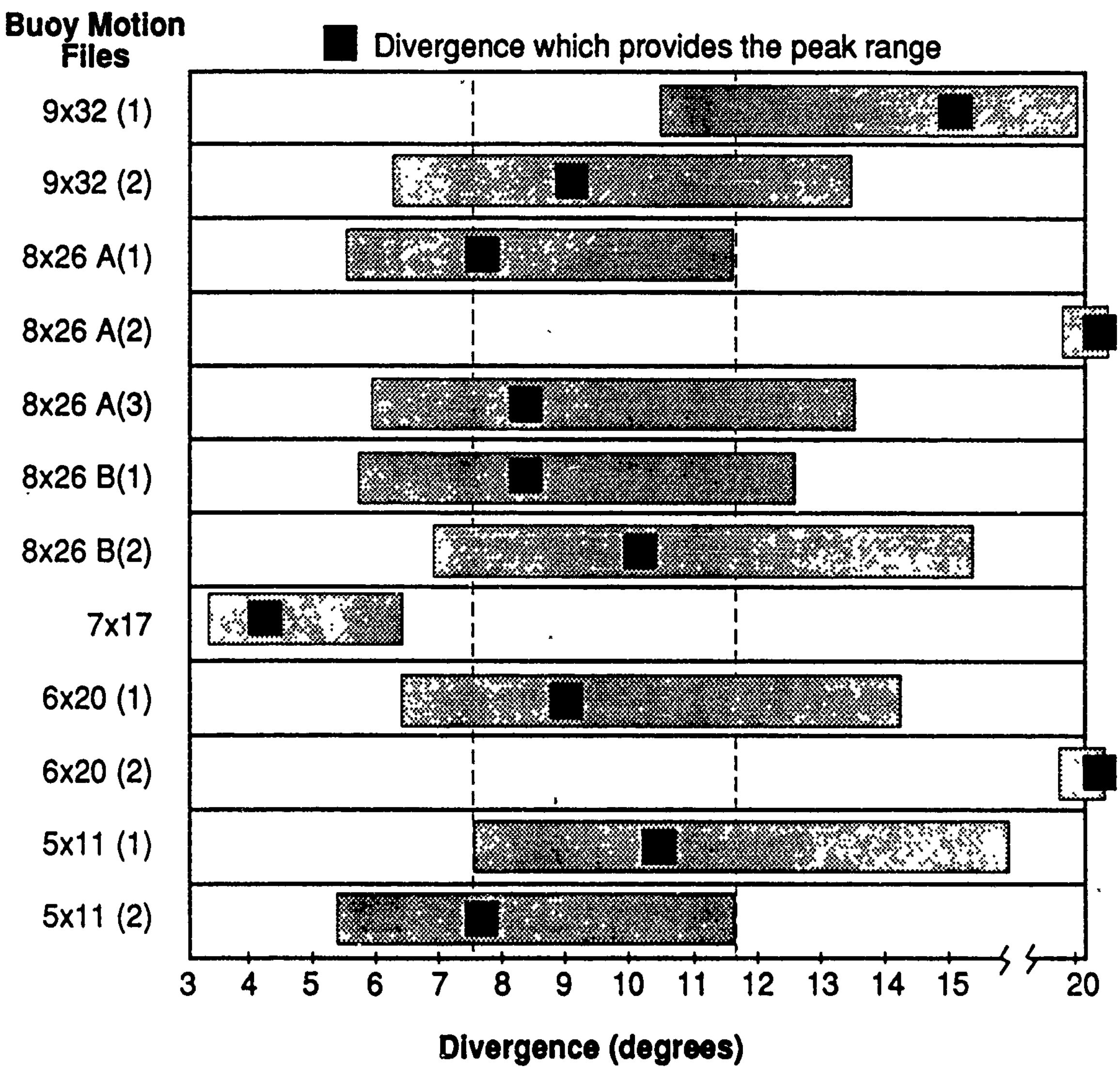

FIGURE 13. Divergences Which Maximize the 80% POD Range for Each Motion File (0.2 nm variance from the peak)

For comparison to the standard Coast Guard optic divergence of 4.2°, a divergence of 9.0° was selected for 80% POD maximization. Of course, when the divergence of a lantern is increased, the nominal range is decreased. The nominal range of a lantern with 9.0° divergence and a flashing 4 characteristic is 5.0 nm. Table 8 provides the estimated 80% POD range which would be achieved with a lantern of 9.0° divergence and provides the percentage of the new nominal range achieved by this lantern.

From Tables 6 and 8 we can see that, on average, an increase in the divergence from 4.2° to 9.0° will increase the 80% POD range by nearly 1.1 nm. This increase will be realized even though the nominal range of a 9.0° lantern will be decreased from 6.0 nm to 5.0 nm. It seems counter-intuitive that an increase in the probability of detection can be attained when the nominal range of a lantern is decreased. This suggests that the validity of using nominal range as a performance rating of our signals must be questioned.

Another finding from this analysis is that list strongly influences detection range. The correlation between list and POD is found to be -0.90 (correlation range: +1 to -1). The correlation between RMS roll and the POD is -0.45. Negative correlations indicate that an increase in either value leads to a decrease in the other. With a list correlation of -0.90 and a roll correlation of -0.45, the influence of list on the POD calculations is more severe than roll. Realistically, we may consider the "buoy motion problem" to be more of a "buoy list problem."

Of course, a lantern divergence of 9.0° will not maximize the 80% POD range for <u>every</u> buoy. In this study, only 8 of the 12 80% POD curves are maximized with a 9.0° divergence. However, 11 of the 12 80% POD ranges have increased with the increase in lantern divergence. The one anomaly, the 7x17 buoy, peaks between 4° and 6° and declines continuously thereafter as divergence increases. The standard lantern divergence of 4.2° would provide the best 80% POD range for this particular buoy motion file.

In two instances the 80% POD range continues to increase as divergence increases (see Figures 8 and 10). The lists associated with these three curves are 7.4° and 6.9°, respectively. The divergence which maximizes the 80% POD range for these two curves falls above 20°. However, as mentioned previously, the list of a buoy fluctuates with time. We see in Table 4 that the 8x26 buoy with a list of 7.4° has had lists of 2.8° and 2.9° on different viewing occasions. Also, the 6x20 buoy with a 6.9° list had a list of 3.0° during a different viewing.

TABLE 8

EFFECT OF ROLL AND LIST ON THE PROBABILITY OF DETECTION

LANTERN DIVERGENCE 9.0°

BUOY	SAMPLE NO.		80% POD RANGE nm	PERCENTAGE OF THE NEW NOMINAL RANGE (5.0 nm)
9 x 32	(1)		3.28	65.6
	(2)		4.36	87.2
8 x 26-A	(1)		4.47	89.4
	(2)		2.40	48.0
	(3)		4.37	87.4
8 x 26-B	(1)		4.42	88.4
	(2)		4.18	83.6
7 x 17	(1)		4.80	96.0
6 x 20	(1)		4.28	85.6
	(2)		1.16	23.2
5 x 11	(1)		4.02	80.4
	(2)		4.50	90.0
		Average	3.85	77.1

The high list values of the two buoys previously mentioned and the stable conditions of the 7x17 buoy remind us that we are dealing with nature. A large collection of random forces act on a buoy at any given time and we can only hope to compensate for a majority of the conditions. A divergence of 9.0° would provide this compensation but would not maximize the detection range in every situation.

6.2 Validity of Assumptions

Conclusions that can be drawn from the data presented here depend upon the validity of the assumptions. Over ten hours of buoy video recordings were used to create the twelve buoy motion files used in this study. The video samples represent all buoy types in a wide range of sea and weather conditions. We assume that buoys in similar conditions, regardless of their location, will roll and list to the same extent. Therefore, we conclude that the twelve samples adequately represent the entire buoy population and can be used to describe buoy motion as a whole (assumption h).

We assume that the effects of buoy motion are equivalent in all observation planes (in every direction) from the buoy (assumption a). The direction of wave and tidal currents acting on a particular buoy may cause more movement in one specific direction over any other. We attempted to minimize this effect by selecting buoys exposed to the open ocean. Therefore, the directionality of movement is not a factor.

The analysis also assumes that the observer knows where to look for the buoy (assumption b). The observer looks in this direction continually for the duration of a flash. Weather conditions during these observations are always the same, 10 nm visibility with negligible background lighting (assumptions f and g). These three assumptions serve to increase the 80% POD range above that which would be experienced under any conditions of restricted visibility or viewing against background lights. However, these assumptions must be allowed to provide a set of standard conditions with which to make calculations. Including the random fluctuations in transmissivity and background lights coupled to an observer scanning for the signal would serve to make any calculations extremely difficult.

Ignoring lamp nigrescence (assumption c) in the calculations is driven by two factors. The first is the algorithm complexity involved in making these calculations. The second is that the rate of intensity modulation in a flash is much slower than lamp nigrescence times. Note that the inclusion of lamp nigrescence would slightly reduce the 80% POD ranges.

We must accept that the Schmidt-Clausen method [Ref. 4] can be used to accurately calculate the effective intensity of a flashing light (assumption d).

Assumption e is a statement of the obvious. Simply put, if a light can be seen at a given distance, it can always be seen at a shorter distance under identical conditions.

Finally, the intensity profiles were estimated with Gaussian curves (assumption i). It is clear from Figure 5 that the actual intensity profile is not a perfect Gaussian. However, it would be difficult, if not impossible, to construct curves which would model the actual intensity profile of a lantern with various degrees of divergence. It is believed that the Gaussian approximations accurately show the relation between POD range and divergence angle. Therefore, changing the divergence angle may not produce the exact 80% POD range presented here, but the change will produce a proportional change in the POD range.

6.3 Agreement with Previous Work

The work presented here is a continuation of work started by Brown, Reference 3. In his report, "PROBABILITIES OF DETECTION AND RECOGNITION OF FLASHING LIGHTS ON ROLLING BUOYS," U. S. Coast Guard Research and Development Center, Report No. CG-D-10-88, August 1987, he concluded that:

1. Detection ranges (90% POD) are as little as 30% of the published nominal range.

2. The most commonly used characteristic, FL 4(.4), on an 8x26 buoy has an effective range of only 1/3 (33%) of the published nominal range.

3. Doubling lantern vertical divergence will nearly double the effective range of floating aids to navigation with a 10% duty cycle.

4. Not only does amplitude of buoy roll degrade signal effectiveness, but so does correlation between period of buoy roll and flash rhythm.

The analysis presented here supports Brown's conclusions 1, 2, and 3. Note that the POD of interest for Brown was 90%. When the POD is decreased to 80%, the 80% POD range will increase. Therefore, the average 80% POD range of 2.8 nm presented in Table 6 (47% of the published nominal range), supports Brown's conclusions 1 and 2.

Brown's conclusion 3 is supported by this study. Brown did not fully analyze the dependence of POD on lantern divergence. His conclusion that divergence should be doubled (8.4° divergence) is in close agreement with the findings of this report (9.0° divergence recommended). However, our findings support a 40% increase in the effective range versus Brown's 100% increase.

Conclusion 4 in Brown's report, the relation between buoy roll period and flash rhythm, was not reviewed in this study.

An important difference in procedure exists between Brown's report and this analysis. Brown emphasized observer view time as a major variable in the detection and recognition of a buoy signal. A 12 second view time was used as a standard for comparison, especially in the computation of recognition probabilities which requires the observation of multiple flashes.

The analysis presented here deals solely with the probability of detecting a <u>single flash</u> given a moving buoy. Either the flash is detected or it isn't, there is no opportunity to view the next flash sequence. For this reason, the poor performance of an FL6 characteristic in Brown's study does not become evident in this analysis. Instead, the slightly longer flash duration of the FL6 characteristic improves the probability of detecting this flash characteristic in any one given cycle when compared to any one cycle of any other flash characteristic with a shorter flash duration.

Finally, the absence of buoy list in Brown's report caused us great concern. Further investigation revealed that the motion recording equipment and associated software used by Brown removed list from the data he recorded. It is for this reason that he did not encounter list in his study, nor did he realize the severe impact list has on the detection probabilities of floating aids.

7.0 CONCLUSIONS

Is buoy motion a problem?

Yes, buoy motion is a problem. Buoy roll and list, particularly list, adversely influence the mariner's ability to detect a signal light at sea. Buoy roll and list are present in all but the calmest of atmospheric and sea conditions.

How severe is the buoy motion problem?

Buoy motion is a combination of the list and the roll of a buoy. In 3 of 12 cases buoy list was is excess of 5.0°. A list of this magnitude coupled with a 4.2° lantern divergence render the light signal of a navigational aid useless.

What can be done to reduce the effects of buoy motion?

While buoy roll is related directly to the sea conditions, buoy list is not. Buoy list must be reduced, eliminated, or compensated for to improve buoy signal effectiveness. Some of the effects of roll and list can be compensated for by adjusting the divergence of the buoy lantern. An increase in divergence from 4.2° to 9.0° will increase the average 80% POD range from 2.8 nm to 3.9 nm, an increase of approximately 40%. However, there will still be occasions when the list and roll amplitudes will so great as to negate the effects of the increased lens divergence.

Is there a relation between nominal range and detection range?

No, the nominal range is simply the range at which the lantern peak intensity is reduced to 0.67 sea-mile-candela when the visibility is assumed to be 10 nm. While computations of detection range in this study also assume a visibility of 10 nm, the calculated detection range accounts for the motion of the buoy. Hence, the nominal range is not a realistic measure of the detection range of a lighted buoy.

8.0 RECOMMENDATIONS

We recommend the Coast Guard:

- Increase buoy lens divergence to 9.0°.

- Study present buoy mechanics to determine the forces which act on a buoy to cause list and then make design changes to alleviate those forces.

9.0 REFERENCES

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